Visual Inspection of Tube Internal

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Abstract: Pipe inspection has a great importance to ensure safety for the nuclear power plant. In this paper, we designed visual inspection module for the tube internal, which diameter is 15~20mm. And we made inspection module which consisted of CCD camera and light. And the relation between image and real world coordinate is established. Image processing is performed to calculate mapping parameter and analyze the size of defect. For the calculation of mapping parameter, experiment is performed using grid type test pattern. Acquired image is processed to extract image coordinate. Edge detection, thresholding, median filtering and morphology filtering is applied to extract grid pattern. Extracted image coordinate is used to calculate image to real world mapping. Lens distortion was considered and corrected to get exact data. Coordinate transformation data is provided for the users to recognize easily. Experiment was performed using grid type test pattern, we extracted lens distortion parameter and real coordinate of defect point. Radial distortion of lens was corrected but tangential distortion was not considered. As continuum to this study, the tangential distortion of lens is considered and improvement of analy zing technique for the tube internal be explored continuously.

Keywords: lens distortion, tube internal, reconstruction, overlap image

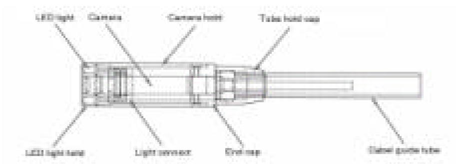
1. INTRODUCTION

In the nuclear power plant, steam generator tubes are U-shaped, feeding the water back to the pipes at the outlet of the steam generator to be recirculated back to the reactor. The height of each tube row may exceed 10m. In the steam generator, the tube carrying the superheated water are quenched with cool water, which generates the steam which drives the turbine to produce electricity. This procedure for generating steam presents several problems. The water used to quench the tubes often has impurities and chemicals which may corrode both the steam generator tubes and the support plates and lead to other damage. Even though periodic inspections of nuclear steam generators are required for compliance with safety regulations, monitoring steam generator cleanliness remains a problem. The highly corrosive environment of the steam generator is particularly problematic for many of the older nuclear reactors in service throughout the world.

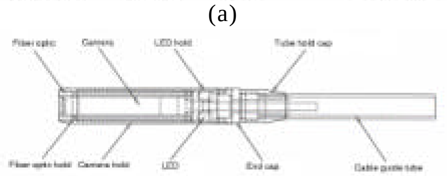
The interior surfaces of tubes are subject to mechanical defects and occasional corrosion. Steam generator tube is designed small diameter to gain maximum heat efficiency. Steam generator tube is put in the hazardous condition, so could not avoid deterioration by erosion and mechanical defect. The damage of steam generator tube is inspected by non-destructed method such as eddy current and ultra-sonic method. They are good method for the detection of damage, but have limits to the materials or shape of contact. Visual inspection is another method to inspect internal side of tube. In this paper, we proposed visual method to inspect tube internal which diameter is 15 20mm. We made inspection module which consisted of CCD camera and LED light. And image processing was performed to analy ze the size of defect. Lens distortion was considered and corrected to get exact data. Coordinate transformation data is provided for the users to recognize easily. Experiment was performed using grid type test pattern, we extracted lens distortion parameter and real coordinate of defect point. We proposed visual inspection of tube internal with a small diameter. This inspection module is superior to endoscope from the viewpoint of resolution and cost. Radial distortion of lens was corrected but tangential distortion was not considered.

2. VISUAL INSPECTION MODULE

Steam generator tube has small diameter to gain maximum heat efficiency. The visual inspection module for the interior surface of the tubes is designed small diameter suited for steam generator tube which diameter is 15~20mm. For inspecting tube internal, visual inspection module must have a light source because its environment must be dark. We fabricate two type of visual inspection module for the tube internal. One is camera with LED light, the other is camera with fiber optic and LED light. LED type is a 17mm diameter and fiber optic type is 14mm diameter. LED type of light intensity is 10 times brighter than fiber optic type.



(a)



(b)

Fig. 1 Drawing of visual inspection module with (a) LED light (b) fiber optic light.

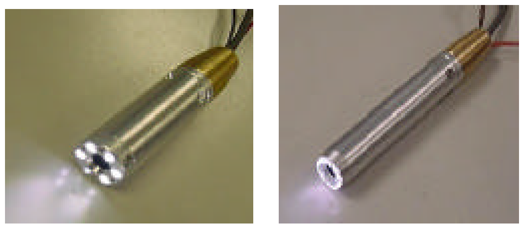


Fig. 2 Visual inspection module with.
(a) LED light (b) Fiber optic light.

Table 1 Specification of visual inspection module.

Parameter	Spec.
Image sensor	1/4" CCD
resolution	470 TVlines
sensitivity	10 lux(F/1.2)
Focal length	2.2mm
FOV	87X67
size	17X74mmm 14X91mm
cable	15m
light	LED :2360lx Fiber optic 371lx

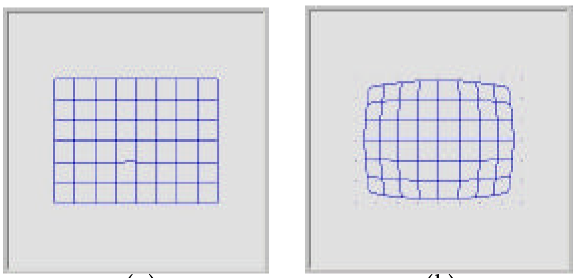
3. VISUAL INSPECTION MODEL FOR THE TUBE INTERNAL

3.1 Lens distortion

For inspecting interior surface of tube, wide-angle lenses are advantage Generally, wide angle lenses have some amount of geometric distortion. These distortions are described with a one-parameter radially symmetric model. Given an ideal undistorted image $f_u(x, y)$, the distorted image is denoted as $f_d(x', y')$, where the distorted spatial parameters are given by :.

$$x' = x(1 + kr^2)\ ,\quad y' = y(1 + kr^2)\ , \tag{1}$$

where $r^2 = (x^2 + y^2)$, and k is the distortion parameter. X is axis, y is vertical axis in image plane and r is the distance. Shown in Fig. 3 are the results of non-distorting and distorting a rectilinear grid with negative values of k. The amount of distortion is typically determined experimentally by imaging a calibration target with known points.



(a) (b)

Fig. 3 Simulation of (a) undistorted image (b) distorted image.

In this paper a technique is presented for extracting the amount of lens distortion with rectilinear grid pattern. The algorithm is simple to implement. Extraction of lens d istortion parameter principle is as follows.

1. assume rectilinear grid pattern
2. assume 3 crossing points with y=0 in undistorted image

$$x_1,\ x_2 = 2x_1 \text{ and } x_3 = 3x_1 \tag{2}$$

3. apply 3 points to distorted image

$$x_1' = x_1 + kx_1^3,$$

$$x_2' = x_2 + kx_2^3 = 2x_1 + 8kx_1^3,$$

$$x_3' = x_3 + kx_3^3 = 3x_1 + 27kx_1^3 \tag{3}$$

4. To eliminate first order term in equation (3), get the interval of grid pattern in distorted image

$$x_2' - x_1' = x_1 + 7kx_1^3,$$

$$x_3' - x_2' = x_1 + 19kx_1^3 \tag{4}$$

5. eliminate first order term in equation (4) by subtraction

$$x_3' - 2x_2' + x_1' = 12kx_1^3 \tag{5}$$

6. substitute kx_1^3 in equation (3) with equation (5), we can get x_1

$$x_1' = x_1 + (x_3' - 2x_2' + x_1')/12 \tag{6}$$

7. we can get distortion parameter k by substituting x_1 in equation (3) with equation (6)

$$k = \frac{D}{(x_1' - D)^3} \tag{7}$$

where $D = \dfrac{(x_3' - 2x_2' + x_1')}{12}$.

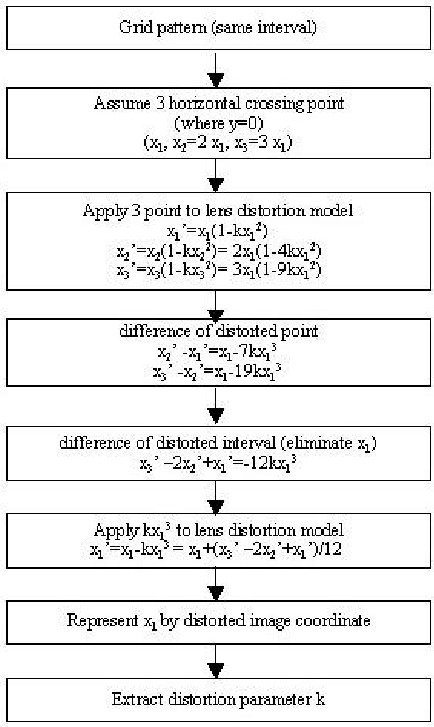


Fig. 4 Flow chart for the extraction o f distortion parameter.

To extract crossing points, image processing operations are performed. Vertical line Edge detection, binary operation and morphological filtering is used. Fig. 5 shows image processing for the extraction of crossing point and Fig. 6 shows extraction of lens distortion parameter and correction of lens distortion.

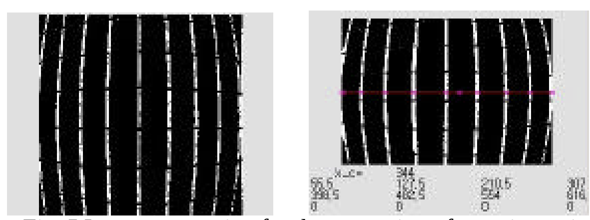
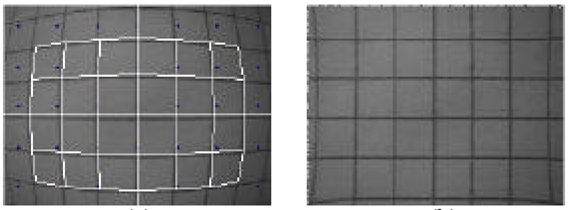


Fig. 5 Image processing for the extraction of crossing point.



(a) (b)

Fig. 6 Extraction of lens distortion parameter and correction of lens distortion.

3.2 Visual inspection model for the interior surface of tube

Image of tube internal seems perspective, so the size of objective differs from the distance between camera and objective. Fig. 6 shows the concept of the visual inspection for the tube internal. The camera model is assumed as pinhole camera model, and optical axis is passed through center of the tube. Let points in the surface of tube internal P_1, P_2, P_3 have same interval and are positioned perpendicular to optical axis Z. The image of the points on the surface of tube internal is appeared in the image plane as P_1', P_2', P_3'. By using the relationship between the points in the real plane and the points in the image plane, we can get the position and the size of any points in the surface of tube internal.

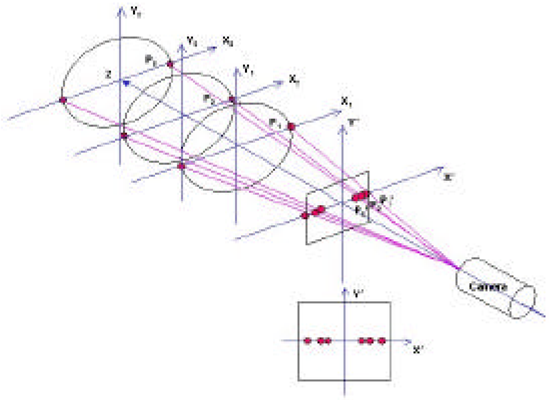


Fig. 7 Concept of the visual inspection for the tube internal.

The 3-dimensional real image in the surface of tube internal is placed to the2-dimensional image sensor plane by the perspective mapping. The left side of Fig. 7 shows the image of tube internal which has rectilinear grid pattern and the right side of Fig. 7 shows the relationship between distance from camera to object in the real world and the distance of rectilinear grid from center in the image plane. An object is farther from camera then the size of image is smaller and the position of image is approach to the center.

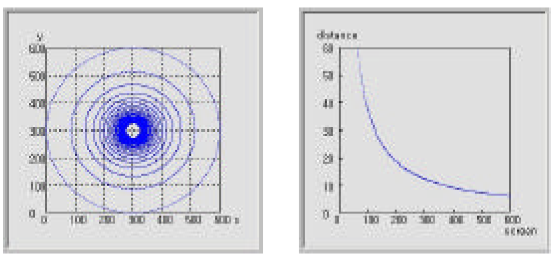


Fig. 8 Image of tube internal and relationship between distance and image plane.

The relationship between real world and image plane is calculated by triangular method. Let us consider a point in the surface of tube internal P and corresponding point in the image plane P', the points have a proportional relationship in the viewpoint of camera. The angle between optical axis Z and the points in the real world and image plane is represented by

$$\tan\alpha = z/R_p, \quad (8)$$

$$r = i/\tan\alpha = R_p \cdot i/z, \quad (9)$$

where α is the angle between starting point in the lens center and target point in the surface of the tube internal, Rp is the radius of tube, and Z is distance between lens and object, and r is distance between image center and target image point.

We considered the relationship between real world and image plane by pinhole camera model so far. However, putting a theory in the practice, the camera model is altered by wide angle lens and the equation. We should modify the image model in equation (9) by considering lens distortion. Fig. 9 shows virtual grid applying to real image of tube internal with pinhole camera model and lens distortion corrected model.

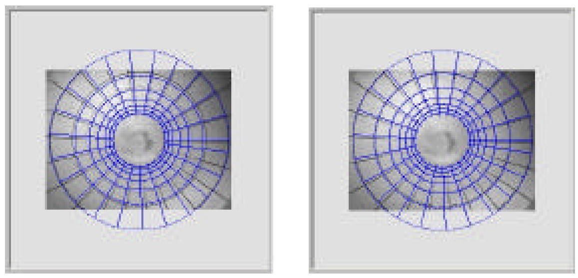


Fig. 9 Virtual grid applying to real image of tube internal (a) pinhole lens model (b) lens distortion corrected model.

3.3 Image reconstruction by coordinate transform

The image of tube internal is represented by the form of polar coordinate. It is difficult to recognize directly the size and position of defect in the acquired image of tube internal. So the acquired image needs to be reconstructed for easy analysis. Fig. 10 shows polar coordinate representation of rectilinear grids and its transform to Cartesian coordinate. In this paper, we reconstruct polar coordinate form of image to Cartesian coordinate form, the image is represented by degree and distance.

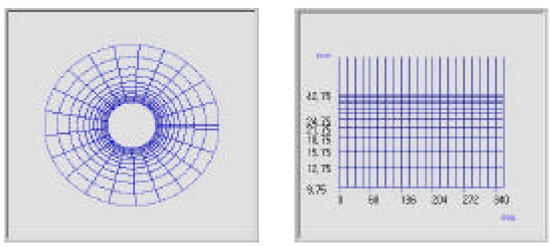


Fig. 10 Simulation of image reconstruction.

A mapping between a polar plane and a rectangular plane They are related to the conventional Cartesian reference system by

Given an polar coordinate image $f_u(x_p, y_p)$, rectangular coordinate image $f_u(x_r, y_r)$

$$x_p = r \cdot \cos\theta, \qquad (10)$$

$$y_p = r \cdot \sin\theta, \qquad (11)$$

where x_p, y_p is horizontal and vertical axis in polar coordinate plane.

The transform of polar coordinate to rectangular coordinate is

$$x_r = \theta \qquad (12)$$

$$y_r = r \qquad (13)$$

where x_r, y_r is horizontal and vertical axis in the rectangular coordinate plane.

4. EXPERIMENT AND RESULTS

For the experiment of visual inspection, we make rectilinear grid pattern which interval is 5mm, and extract the parameter of lens distortion. The parameter of lens distortion k is 0.0402. Fig. 11 shows experimental setup for visual inspection of tube internal.

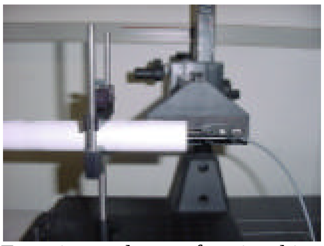


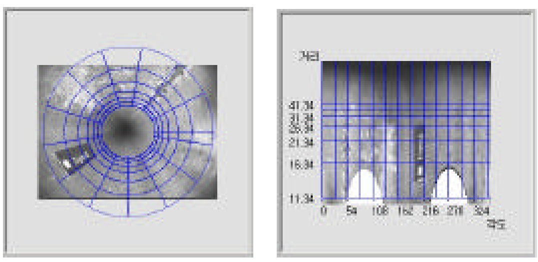
Fig. 11 Experimental setup for visual inspection.

In the experiment, we extract the crossing point of rectilinear grid pattern. Table 2 shows the result of errors for the extraction of rectilinear grid interval. Interval 1 is the interval between first and second grid pattern and interval 2 is the interval between second and third grid pattern from center of the image. The errors occur more significant the outside of the image center. And comparison of the lens distortion, the result with considering lens distortion appears three or four times accurate than without considering lens distortion.

Table 2 Errors with or without considering lens distortion.

	Errors when without considering distortion	Errors when considering distortion
Interval 1	0.43mm(8.6%)	0.11mm(2.2%)
Interval 2	0.77mm(15.4%)	-0.25mm(5%)

Another experiment is performed by using real tube which diameter is 21mm, and we insert a sample pattern which size is known. Reconstructed image is produced and virtual grid is overlapped with the acquired image and processed image. The interval of virtual grid is varied with any size, and interval of 5mm and 3mm virtual grid is used in the experiment. By the result of this technique, the image for the tube internal can be analyzed more easily.



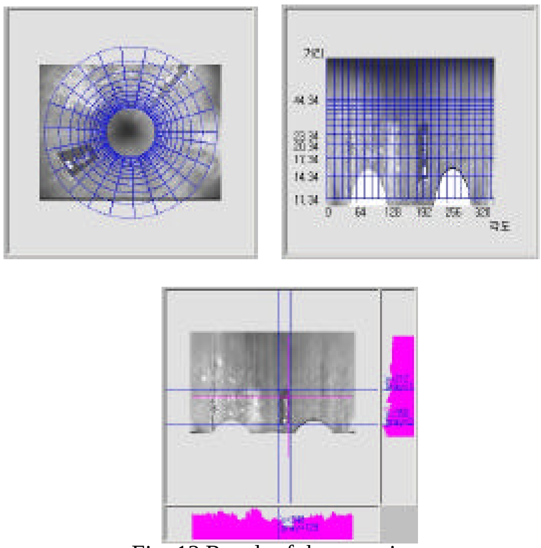


Fig. 12 Result of the experiment.

5. CONCLUSION AND FUTURE WORK

In this paper, we proposed visual method to inspect tube internal which diameter is 15 20mm. We made inspection module which consisted of camera and light. And image processing was performed to analyze the size of defect. Lens distortion was considered and corrected to get exact data. Coordinate transformation data is provided for the users to recognize easily. Experiment was performed using rectilinear grid test pattern, we extracted lens distortion parameter and real coordinate of defect point. This inspection module is superior to endoscope from the viewpoint of resolution and cost. Radial distortion of lens was corrected but tangential distortion was not considered. As continuum to this study, the tangential distortion of lens is considered and improvement of analyzing technique for the tube internal be explored continuously

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REFERENCES

[1] H. Farid and A.C. Popescu, "Blind removal of lens distortion," *Journal of the Optical Society of America A*, 2001.

[2] J. Weng, "Camera calibration with distortion models and accuracy evaluation," *IEEE Transactions on Pattern Analysis and Machine Intelligence*, 14(10), pp.965-979, 1992.

[3] F. Devernay and O. Faugeras, "Automatic calibration and removal of distortion from scenes of structured environments," *SPIE Conference on Investigative and Trial Image Processing*, 1995

[4] M. Kolesnik, G. Baratoff, "3-D interpretation of sewer circular structures," *Proceedings of the 2000 IEEE International Conference on Robotics & Automation*, pp. 1453-1458, 2000.